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Review

Development of high flux solar simulators for solar thermal research

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A R T I C L E I N F O

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A B S T R A C T

High flux solar simulators, used to produce controlled high temperature experiments are a valuable tool for the research and development of high temperature material processes. As an alternative to a direct external solar concentrator where the sun's radiation is concentrated using a parabolic dish, an indoor solar simulator uses an array of high intensity discharge lamps attached to ellipsoidal mirrors to focus their light at a secondary focal point where temperatures in excess of 2000 °C can be reached. To mimic, as closely as possible, the spectrum of the sun, a novel high flux solar simulator design using metal halide lamps has been constructed. The 42 kW_e simulator consisting of seven 6 kW_e metal halide lamps delivered a peak thermal flux of approaching 1 mW/m^2 to the secondary focal plane of a closely coupled ellipsoidal reflector. A comparison of different designs and their performance is also presented in this paper.

Contents

1. Introduction

The application and design of solar simulators falls into two main classifications, non-concentrating uniformly distributed light used in the testing of photovoltaic (PV) cells and solar hot water collectors and high flux concentrators used to generate high temperatures exceeding 1000 °C used for a variety of research applications including material processing, thermo-chemical reactions, the production of solar fuels and in simulated solar thermal power generation. The radiation heat source needs to resemble as closely as possible the spectrum of the sun and in the main has been a high intensity arc lamp coupled to an optical reflector resulting in the delivery of an intense beam of concentrated radiation with wavelengths in the UV, visible and infrared regions of the spectrum. As early as 1973 researchers [1] inserted a tungsten–halogen heat source positioned at one focus of a suitably shaped ellipsoidal reflector to heat small objects placed at the secondary. High flux solar simulators first began to appear in the early 1990's in the USA using xenon lamps [2]. Argon arc lamps and high powered xenon lamps were used in 2003–2007 at ETH Zurich [3,4]. By 2012 high intensity solar simulators were used in research centres [5–8] that were capable of generating intense fluxes and concentrations of over 4000 suns all using

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xenon lamps that were close coupled to a precision ellipsoidal mirror.

Optical configurations based on parabolic-shaped mirrors are commercially available for large-scale collection and concentration of solar energy for the generation of electrical power. The total amount of radiated power collected by any of these systems is proportional to the projected area of the mirrors. Their arrangement depends mainly on the concentrating system selected and the latitude of the site [9]. The most common configurations used for concentration of the sun's energy in solar thermal applications are linear concentrators such as parabolic troughs and Fresnel concentrators, or point concentrators such as the central solar towers and parabolic dishes. An alternative reliable research tool is required that is capable of providing an artificial source of concentrated energy with a spectral distribution as close as possible to that of natural sunlight. A high flux solar simulator will create the constant conditions required for controlled high temperature experimentation. At the same time the design objectives must be to simulate the parameters that would be encountered by high concentration solar systems capable of processing materials on commercially viable scale including the spectral distribution and a large focal hot spot of the reflected sun image. Metal halide lamps are unique in how their spectral distribution closely replicates sunlight and their larger arc length results in less intense regions of high flux [3].

This paper describes the design and fabrication of a high concentration solar simulator using an array of seven high powered metal halide lamps each coupled to a precision ellipsoidal reflector.

2. Design

Factors that were taken into consideration during the design stage included costs, the emission spectrum of the lamp, the lamp efficiency, lamp cooling, reflector size, shape and quality, reflector surface coating, the positioning of the lamp within the reflector, reflector support and safety. From a comparison of the lamps used in high intensity solar simulators, the xenon lamp has clearly been the preferred choice for two main reasons, the radiation spectrum and the size of the arc light source. The spectral distribution of the suns radiation is shown in Fig. 1.

The bulk of the energy is within the visible light wavelength of 350–700μm sharply falling off in the UV region and a more gradual fall in the near and far infrared. By contrast the xenon lamp emission spectrum shown in Fig. 2 shows a flat low energy distribution profile in the visible light region with a number of intense spikes in the infrared [10].

The visible light emission constitutes about 25% of the total light output, with most of the energy falling into the infrared spectral region. Approximately 70% of the xenon arc lamp output occurs at wavelengths longer than 700 nm, while less than 5% of the output consists of wavelengths less than 400 nm. Similarly with the argon arc lamp in Fig. 3 below showing low energy emission in the visible light region of 380–700 nm and high energy emission spikes in the 700–1000 nm range.

By contrast the metal halide lamp spectral distribution is very similar to that of natural sunlight shown in Fig. 4. The distribution profile is quite similar to that of sunlight except for a spike at 850–950 nm. The high energy component of the radiation is contained within the visible range of the spectrum from 400–800 nm. The metal halide lamp is an artificial light source that emits a radiation spectrum that closely mimics that of natural sunlight. The intense infrared energy spikes that xenon lamps emit require either forced air cooling for low wattage lamps or water cooling for higher powered lamps. In addition the reflectors are more prone to damage and may require forced air cooling to their surface.

With metal halide lamps by contrast approximately, 90% of the electrical energy supplied to the lamp is converted to and radiated out as energy, and the remaining 10% is lost through ohmic effects to the foils and electrodes. About 75% of the power consumed is radiated by the discharge arc itself. This radiation output, illustrated in Fig. 5, is split up into the 10% UV, 45% visible and 20% infrared radiation. Around 15% of the energy is emitted by the electrode and the bulb which can reach temperatures of more than 900 °C [10].

As the arc size within the lamp increase, the transfer efficiency of radiative energy originating at the arc that reaches the target is reduced [3,11]. This negatively affects the magnitude and distribution of the radiative flux in the target plane. For this reason even though the metal halide lamp emits a spectral distribution that more closely replicates sunlight, xenon lamps have been chosen over metal halide. However the luminous efficacy, which is described as how efficiently a lamp converts electrical energy into visible light, has in the past been very limiting with little choice but to choose a xenon lamp, this is no longer the case [10]. Xenon lamps that have a power range of 4–6 kW have a luminous flux range of 155,000–280,000 lm and an efficacy of 39–47 lm/W. The power equivalent in the metal halide lamp has a luminous flux range of 380,000–600,000 lm and an efficacy of 95–100 lm/W making the metal halide lamp more efficient in converting electrical power to light in this size range. In addition xenon lamps operate under very high pressure and are dangerous in the event of any exploding bulb. Metal halide lamps on the other hand operates at much lower pressures and has a protective outer bulb for added protection. There is a direct relationship between the

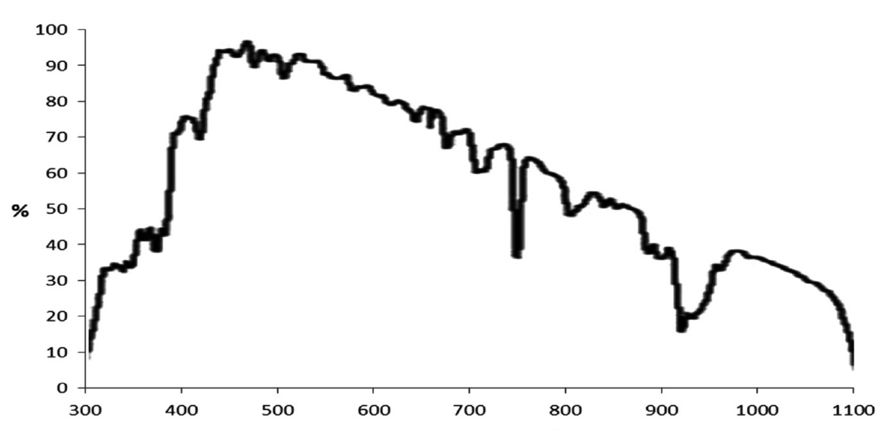

Fig. 1. Solar spectral distribution incident on the earth's surface. (Reproduced from ASTM Terrestrial Reference Spectra).